Moorings Technical Analysis
Client: Kaly
Site: Seaweed Farm

Doc. No.: GFME-TR-090
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Gael Force GROUP

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Revision Control

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Rev.	Date	Originator	Approver	Description
A	03/05/2024	Scott Dickison	A.Young	First Issue

1 Summary

This report describes a Technical Analysis for a seaweed farm arrangement for Kaly.

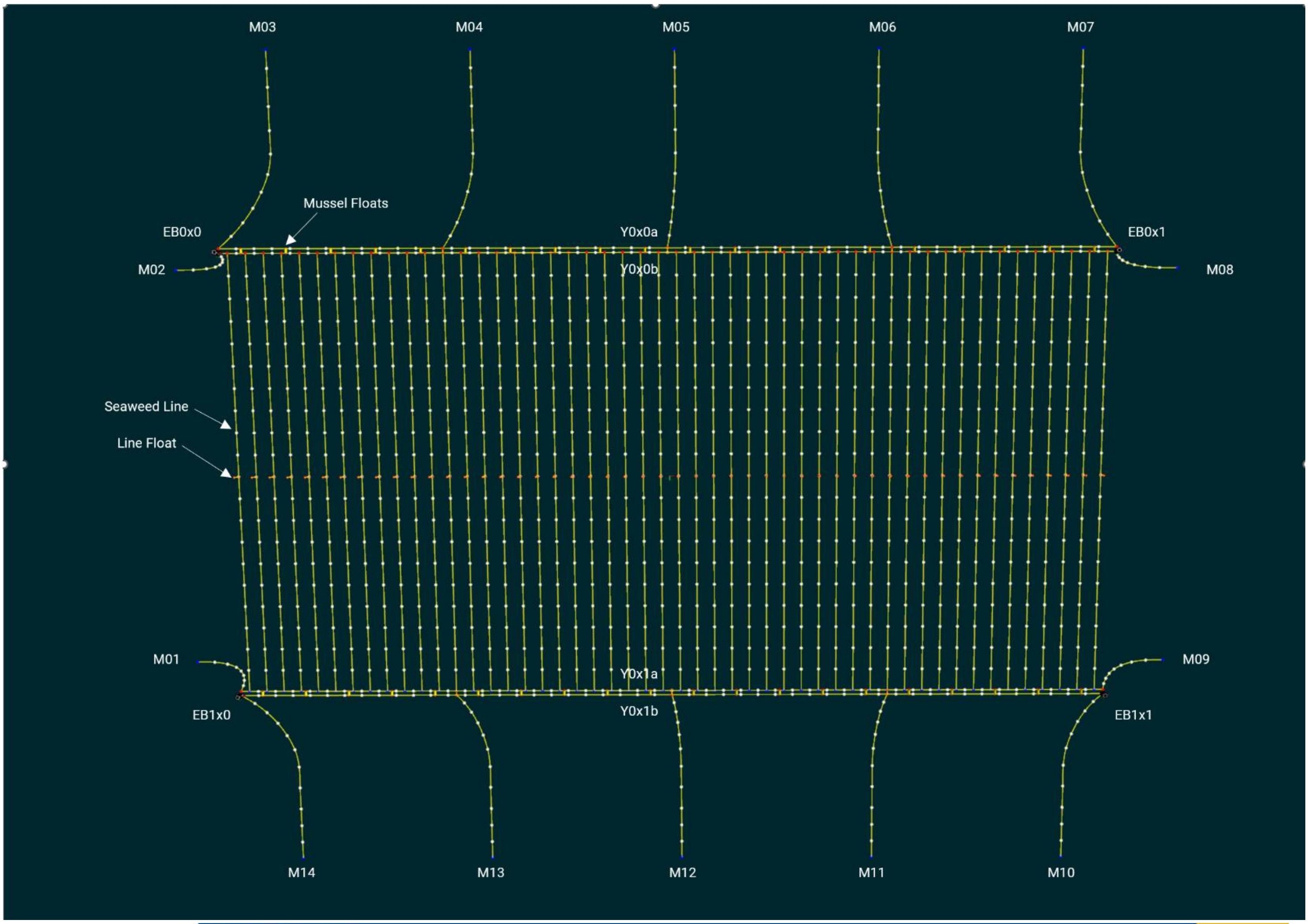
The report describes the applied environmental data, the processing undertaken to enable that data to be used for the analysis, the physical design being analysed, the results of that analysis and the compliance of the design to the design standard requested.

For the purposes of developing a standard system, a set of environments will be applied in all directions. Environment 1 is based on the 50 year current in Loch Snizort, with a typical wind speed and sheltered wave. This environmental case has been processed using the guidelines in Scottish Technical Standard for Finfish Aquaculture. An additional 2 environments have been modelled to indicate the performance of the grid across a range of sheltered conditions.

The tables below show the highest loaded lines in the harvest state of environment 1 and their factors of safety compared with the requirement of the standard for a given material.

Line	Segment	Max Tension ULS (T)	Min FOS ULS	Found in	ULS Material Factor
Mooring02	PolySteel_3_Strand_32	11.44	1.42	ULS01	3.00
	U2_StudLink_32	11.44	5.19	ULS01	2.00
GridlineY0x0a	PolySteel_3_Strand_32	4.17	3.90	ULS01	3.00
GridlineY0x0b	PolySteel_3_Strand_32	6.75	2.41	ULS01	3.00

It is recommended that embedment tests should be carried out at all intended anchor locations to ensure the expected holding power of the anchor can be achieved.



2 Introduction

Gael Force Group has been instructed to carry out a Technical Analysis for Kaly for a seaweed farm design. The Site consists of 4 rectangular grids, independently moored, with space allowance for creel fishing corridors.

This document outlines the inputs and results from a full technical dynamic analysis for the above system design. It will describe the physical system parameters and environmental conditions used as the basis for the design, and adjustments required by the applied design standard. All system loads are identified and evaluated.

3 Design Basis

3.1 Assumptions

The following assumptions have been made in preparing and undertaking this analysis –

1. Seabed depth of 20m
2. A seaweed model has been determined based on physical data from SINTEF research organisation.
3. No effects of current shadowing have been considered.
4. The requirement of each component will be the same for those in symmetrical positions

3.2 Applicable Design Standard

The system has been analysed applying the requirements of Scottish Technical Standard for Finfish Aquaculture. This is for environmental processing only and as a reference for possible equipment assignment. Forty-two simulations have been undertaken which are referred to as Ultimate Limit State (ULS) simulations. These consist of the applied environment in eight directions for the first environmental case and 3 for each additional environment to cover 3 unique directions for this symmetrical arrangement as well as three growth states for the seaweed. These are starting mass, mid growth and harvest growth.

The results of these simulations are post-processed to identify the highest load scenario for every component within the system.

The loads on every component are then compared to the Minimum Break Load specified for that component to confirm it complies with all the minimum factors of safety specified within the Standard.

It has been assumed that all anchors are fully embedded and are therefore considered as being fixed points.

3.3 Environmental Conditions

Table 1: Maximum combined waves (wind waves & ocean waves)

Environment:	1	2	3
U (m^{s-1})	34.34	30.00	20.00
H_s (m)	1.05	0.79	0.53
T_P (s)	5.00	4.00	3.00

Table 2: Current

Environment:	1	2	3
V_c (ms^{-1})	0.274	0.2	0.1

3.4 Mooring System

The system as designed for installation at site is identified in the tables below –

Table 3: Mooring Line Details

Mooring Line	Depth[m]	Segment	Segment Length (m)	Anchor Weight [T]
Mooring01		PolySteel_3_Strand_32	46.25	Helical
Mooring01		U2_StudLink_32	13.75	
Mooring02		PolySteel_3_Strand_32	46.25	Helical
Mooring02		U2_StudLink_32	13.75	
Mooring03		PolySteel_3_Strand_32	46.25	0.5
Mooring03		U2_StudLink_32	13.75	
Mooring04		PolySteel_3_Strand_32	46.25	0.5
Mooring04		U2_StudLink_32	13.75	
Mooring05		PolySteel_3_Strand_32	46.25	0.5
Mooring05		U2_StudLink_32	13.75	
Mooring06		PolySteel_3_Strand_32	46.25	0.5
Mooring06		U2_StudLink_32	13.75	
Mooring07		PolySteel_3_Strand_32	46.25	0.5
Mooring07		U2_StudLink_32	13.75	
Mooring08		PolySteel_3_Strand_32	20.25	Helical
Mooring08		U2_StudLink_32	13.75	
Mooring09		PolySteel_3_Strand_32	20.25	Helical
Mooring09		U2_StudLink_32	13.75	
Mooring10		PolySteel_3_Strand_32	20.25	0.5
Mooring10		U2_StudLink_32	13.75	
Mooring11		PolySteel_3_Strand_32	20.25	0.5
Mooring11		U2_StudLink_32	13.75	
Mooring12		PolySteel_3_Strand_32	20.25	0.5
Mooring12		U2_StudLink_32	13.75	
Mooring13		PolySteel_3_Strand_32	20.25	0.5
Mooring13		U2_StudLink_32	13.75	
Mooring14		PolySteel_3_Strand_32	20.25	0.5
Mooring14		U2_StudLink_32	13.75	

Table 4: Grid Line Details

Grid Line	Segment	Length
Longitudinal Grid Lines	PolySteel_3_Strand_32	200
Transverse Grid Lines	Seaweed Line	100

Table 5: Buoy Details

Buoy No.	Buoy Type	Size (l)
EB0x0	End Buoy	600
EB0x1	End Buoy	600
EB1x0	End Buoy	600
EB1x1	End Buoy	600
Mussel Floats	Mussel Float	200
Line Floats	Polyform	A0

3.5 Modelling

3.5.1 Moorings Analysis Overview

Proteus DS software has been used for computer modelling and simulation of mooring installations. Other software packages are used in the industry however Proteus DS was chosen due to the extensive validation of the software undertaken by DSA, including tank tests, software benchmarks, full-scale comparison and, in conjunction with Gael Force's own comprehensive empirical real-time data sets was considered the most suitable dynamic simulation software for the purpose.

The Finite Element Analysis process does not design a mooring system, it enables the User to analyse a specified design to confirm the loads exerted upon it and the stresses in the components. As such the physical design of the system along with the characteristics of the mooring system components are modelled in the software. The environmental conditions are applied to the model based on the wind, waves and currents, and the stresses within the components are calculated.

As modelled, we have analysed 1 grid of the seaweed farm arrangement. The grid is independently moored. It consists of a pair of headlines (double gridlines) each with 20 headline mussel floats, equally spaced. The headlines are terminated by a 600L buoy at each end. Mooring lines are attached to the headline at the ends and at 50m spacing along the side. The end mooring lines are terminated by helical anchors with a scope of 1.5 while the side mooring lines are terminated be drag anchors with a scope of 3. These headlines support 50 seaweed lines with 4m spacing. Each seaweed line features a midline buoy with a 1.5m connector.

A model for seaweed drag has been created using physical test data found in OMAE2019-96375 CURRENT INDUCED DRAG FORCES ON CULTIVATED SUGAR KELP [(2)]. This document features the chart in Figure 1 - Drag force per meter divided by weight per meter (n) as a function of towing velocity

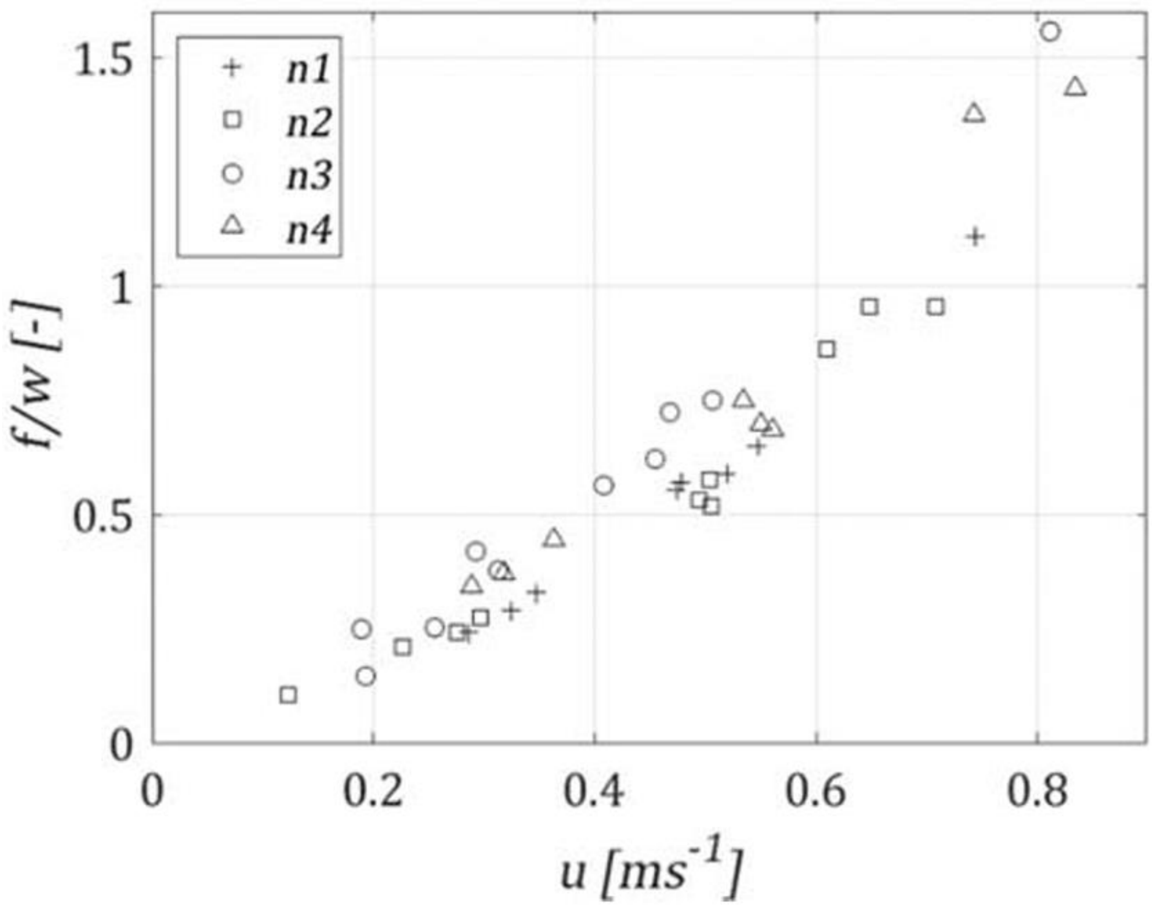


Figure 1 - Drag force per meter divided by weight per meter (n) as a function of towing velocity

Building Stronger

The seaweed line is modelled in proteus as a flexible cylinder with a density of 1024kg/m^3. Diameter is used to set the appropriate mass per meter. This Diameter is used as the wetted area in the drag calculation using the formula:

$$C_d = \frac{2 * F_d}{\rho u^2 * A}$$

Drag is calculated for each mass/m of seaweed at various velocities and a quadratic line of best fit is applied.

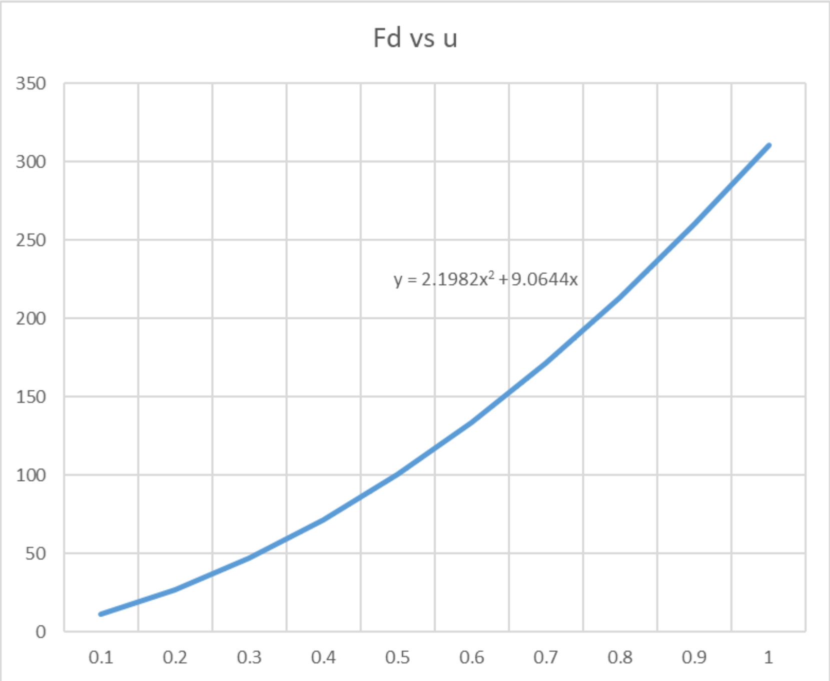


Figure 2 - Drag force as a function of velocity for seaweed at 16kg/m

Assuming zero drag at zero velocity, the equation of the line of best fit is used as input for the linear quadratic drag model in proteus for each analysed growth state. Axial and normal drag has been considered equal.

Seaweed kg/m	LinearNormal DragCoefficient (Ns/m^2)	LinearTangential DragCoefficient (Ns/m^2)	QuadraticNormal DragCoefficient (Ns^2/m^3)	QuadraticTangential DragCoefficient (Ns^2/m^3)
5 (start)	28.33	28.33	68.69	68.69
10 (mid)	56.65	56.65	137.39	137.39
16 (harvest)	90.06	90.06	219.82	219.82

The original data source states "the results of this study may overestimate the drag force rather than underestimate (for growth levels similar to the ones presented in this study) and might therefore still be of interest for dimensioning of seaweed farms". In addition to this, the effects of current shadowing on seaweed lines located behind other seaweed lines is difficult to predict without additional data and has not been included. Therefore, results within this report should be considered as conservative.

The model is run initially with no environmental conditions applied to it, for a simulated period of 30 seconds to allow it to settle to a state of equilibrium, the current is then added for a simulated period of 180 seconds, following which the waves are added for a duration of two times the wave period.

3.5.2 Mooring System Component Identification

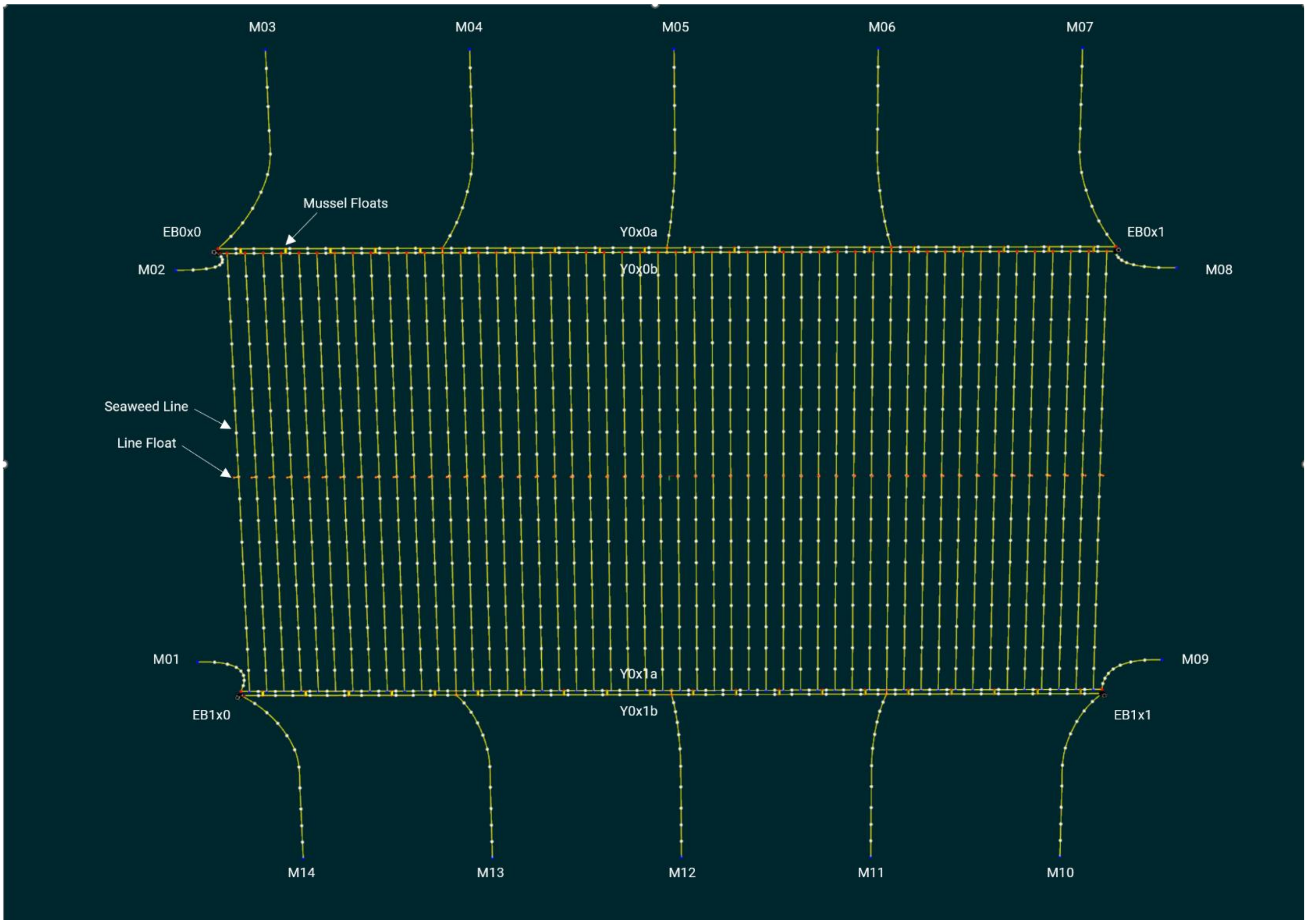


Figure 3 - Mooring System Component Identification

4 Results

4.1 Analyses Condition Inputs

The environmental conditions have been transposed to ensure all parameters follow the same convention in respect of direction.

When applied to the model the wave height is converted to H_{max} by multiplying the H_s value by 1.9. The environmental conditions used for the purpose of analysis are identified in Table 6: Environmental conditions for analyses. Simulations have been assigned into groups that will be processed together and their maximum loads compared.

Table 6: Environmental conditions for analyses

Group	Analysis	Direction (°T)	H_{max} (m)	$T_{p(P\text{-}M)}$ (s)	Wind (ms^{-1})	Current (ms^{-1})
1	ULS01_Harvest_0	0°	2.00	5.00	33.34	0.274
	ULS02_Harvest_45	45°	2.00	5.00	33.34	0.274
	ULS03_Harvest_90	90°	2.00	5.00	33.34	0.274
	ULS04_Harvest_135	135°	2.00	5.00	33.34	0.274
	ULS05_Harvest_180	180°	2.00	5.00	33.34	0.274
	ULS06_Harvest_225	225°	2.00	5.00	33.34	0.274
	ULS07_Harvest_270	270°	2.00	5.00	33.34	0.274
	ULS08_Harvest_315	315°	2.00	5.00	33.34	0.274
2	ULS09_Mid_0	0°	2.00	5.00	33.34	0.274
	ULS10_Mid_45	45°	2.00	5.00	33.34	0.274
	ULS11_Mid_90	90°	2.00	5.00	33.34	0.274
	ULS12_Mid_135	135°	2.00	5.00	33.34	0.274
	ULS13_Mid_180	180°	2.00	5.00	33.34	0.274
	ULS14_Mid_225	225°	2.00	5.00	33.34	0.274
	ULS15_Mid_270	270°	2.00	5.00	33.34	0.274
	ULS16_Mid_315	315°	2.00	5.00	33.34	0.274
3	ULS17_Start_0	0°	2.00	5.00	33.34	0.274
	ULS18_Start_45	45°	2.00	5.00	33.34	0.274
	ULS19_Start_90	90°	2.00	5.00	33.34	0.274
	ULS20_Start_135	135°	2.00	5.00	33.34	0.274
	ULS21_Start_180	180°	2.00	5.00	33.34	0.274
	ULS22_Start_225	225°	2.00	5.00	33.34	0.274
	ULS23_Start_270	270°	2.00	5.00	33.34	0.274
	ULS24_Start_315	315°	2.00	5.00	33.34	0.274
4	ULS25_Harvest2_0	0°	1.5	4.00	30.00	0.2
	ULS26_Harvest2_45	45°	1.5	4.00	30.00	0.2
	ULS27_Harvest2_90	90°	1.5	4.00	30.00	0.2
5	ULS28_Harvest3_0	0°	1.0	3.00	20.00	0.1
	ULS29_Harvest3_45	45°	1.0	3.00	20.00	0.1
	ULS30_Harvest3_90	90°	1.0	3.00	20.00	0.1
6	ULS31_Mid2_0	0°	1.5	4.00	30.00	0.2
	ULS32_Mid2_45	45°	1.5	4.00	30.00	0.2
	ULS33_Mid2_90	90°	1.5	4.00	30.00	0.2
7	ULS34_Mid3_0	0°	1.0	3.00	20.00	0.1
	ULS35_Mid3_45	45°	1.0	3.00	20.00	0.1
	ULS36_Mid3_90	90°	1.0	3.00	20.00	0.1
8	ULS37_Start2_0	0°	1.5	4.00	30.00	0.2
	ULS38_Start2_45	45°	1.5	4.00	30.00	0.2
	ULS39_Start2_90	90°	1.5	4.00	30.00	0.2
9	ULS40_Start3_0	0°	1.0	3.00	20.00	0.1
	ULS41_Start3_45	45°	1.0	3.00	20.00	0.1
	ULS42_Start3_90	90°	1.0	3.00	20.00	0.1

4.2 Evaluation of Simulation Results

The dimensioning loads in the following tables, Table 7: Highest Loaded Mooring Lines , Table 8 Highest Loaded Grid Lines , are identified based on whether the highest load occurs in either an Ultimate Limit State or an Accident Limit State scenario. The component will be dimensioned according to whichever state & environment in which the highest calculated Minimum Break Load is specified. Given the environments have been applied in all directions, it can be assumed that the requirement of each component will be the same for those in symmetrical positions.

4.2.1 Component Line Loads – Harvest State across all environments

Table 7: Highest Loaded Mooring Lines in the Harvest State – Environment 1

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Mooring	Study in which Max Load Obtained	ULS	Rope	Chain / Shackle
		yl = 1.15	ym = 3.00	ym = 2.00
Mooring01	ULS01_Harvest_0	11.44	34.33	22.89
Mooring02	ULS01_Harvest_0	11.44	34.33	22.88
Mooring03	ULS03_Harvest_90	3.79	11.37	7.58
Mooring04	ULS03_Harvest_90	7.68	23.03	15.35
Mooring05	ULS03_Harvest_90	7.56	22.67	15.11
Mooring06	ULS03_Harvest_90	7.68	23.03	15.35
Mooring07	ULS03_Harvest_90	3.79	11.36	7.58
Mooring08	ULS05_Harvest_180	11.44	34.33	22.89
Mooring09	ULS05_Harvest_180	11.44	34.32	22.88
Mooring10	ULS07_Harvest_270	3.81	11.43	7.62
Mooring11	ULS07_Harvest_270	7.72	23.17	15.45
Mooring12	ULS07_Harvest_270	7.58	22.75	15.17
Mooring13	ULS07_Harvest_270	7.72	23.15	15.43
Mooring14	ULS07_Harvest_270	3.81	11.44	7.63

Table 8 Highest Loaded Grid Lines in the Harvest State – Environment 1

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Gridline	Study in which Max Load Obtained	ULS	Rope	Chain / Shackle
		yl = 1.15	ym = 3.00	ym = 2.00
GridlineY0x0b	ULS05_Harvest_180	6.75	20.25	13.50
GridlineY0x1b	ULS05_Harvest_180	4.17	12.50	8.33
GridlineY0x0a	ULS05_Harvest_180	4.17	12.50	8.33
GridlineY0x1a	ULS01_Harvest_0	6.75	20.25	13.50

Table 9: Highest Loaded Mooring Lines in the Harvest State – Environment 2

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Mooring	Study in which Max Load Obtained	ULS	Rope	Coupling plates / Steel coupling elements / Chain
		yl = 1.15	ym = 3.00	ym = 2.00
Mooring01	ULS25_Harvest2_0	7.44	22.33	14.89
Mooring02	ULS25_Harvest2_0	7.44	22.31	14.87
Mooring03	ULS27_Harvest2_90	2.66	7.97	5.32
Mooring04	ULS27_Harvest2_90	5.23	15.70	10.47
Mooring05	ULS27_Harvest2_90	5.14	15.41	10.27
Mooring06	ULS27_Harvest2_90	5.24	15.71	10.47
Mooring07	ULS27_Harvest2_90	2.66	7.98	5.32

Table 10 Highest Loaded Grid Lines in the Harvest State – Environment 2

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Gridline	Study in which Max Load Obtained	ULS	Rope	Coupling plates / Steel coupling elements / Chain
		yl = 1.15	ym = 3.00	ym = 2.00
GridlineY0x0b	ULS25_Harvest2_0	4.35	13.05	8.70
GridlineY0x1b	ULS25_Harvest2_0	2.40	7.20	4.80

Table 11: Highest Loaded Mooring Lines in the Harvest State – Environment 3

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Mooring	Study in which Max Load Obtained	ULS	Rope	Coupling plates / Steel coupling elements / Chain
		yl = 1.15	ym = 3.00	ym = 2.00
Mooring01	ULS28_Harvest3_0	2.44	7.33	4.88
Mooring02	ULS29_Harvest3_45	2.87	8.60	5.73
Mooring03	ULS30_Harvest3_90	1.26	3.79	2.53
Mooring04	ULS30_Harvest3_90	2.30	6.89	4.59
Mooring05	ULS30_Harvest3_90	2.24	6.71	4.48
Mooring06	ULS30_Harvest3_90	2.29	6.87	4.58
Mooring07	ULS30_Harvest3_90	1.26	3.79	2.53

Table 12 Highest Loaded Grid Lines in the Harvest State – Environment 3

		Dim Load(T)	ULS Minimum Breaking Load (MBL)(T)	
Gridline	Study in which Max Load Obtained	ULS	Rope	Coupling plates / Steel coupling elements / Chain
		yl = 1.15	ym = 3.00	ym = 2.00
GridlineY0x0b	ULS29_Harvest3_45	2.20	6.61	4.41
GridlineY0x1b	ULS28_Harvest3_0	0.58	1.73	1.15

4.2.2 Loads across environmental and growth states

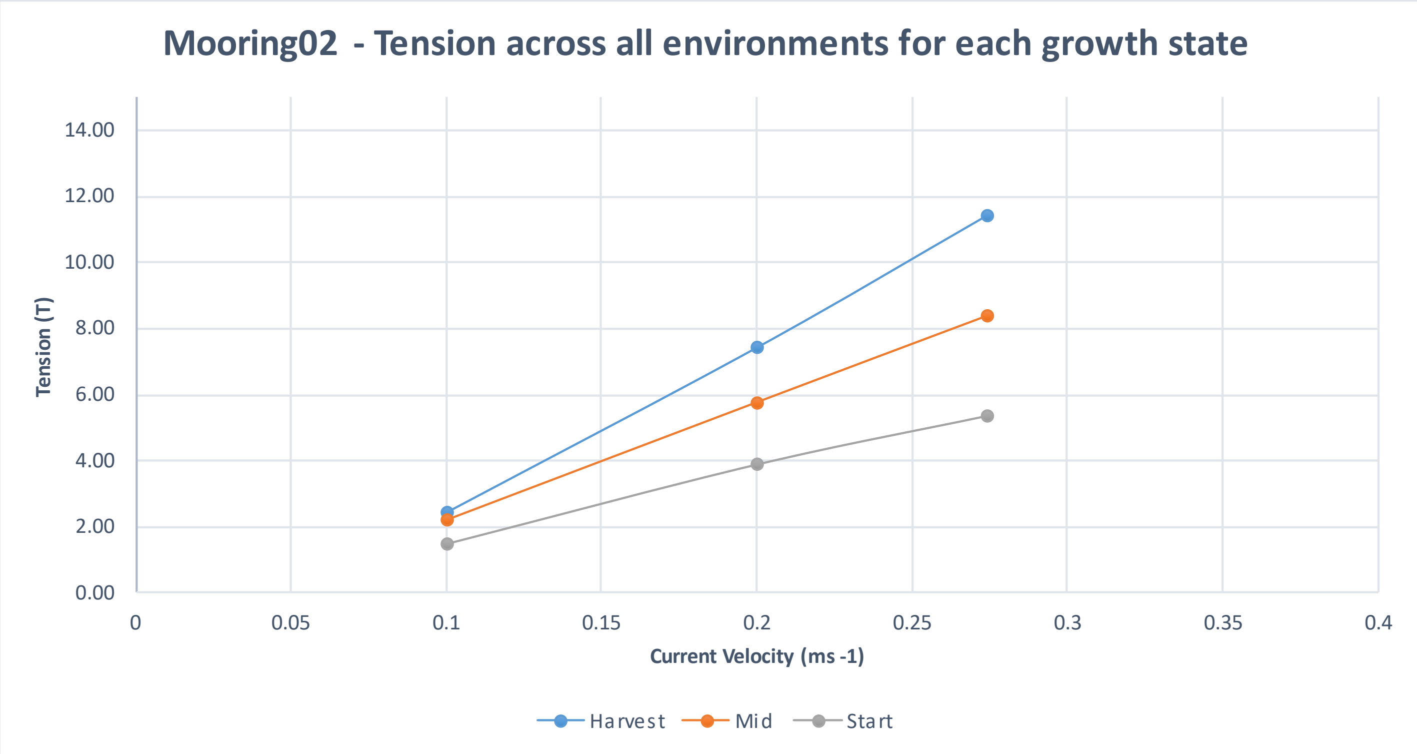


Figure 4 - Highest Loads in Mooring02 across all states

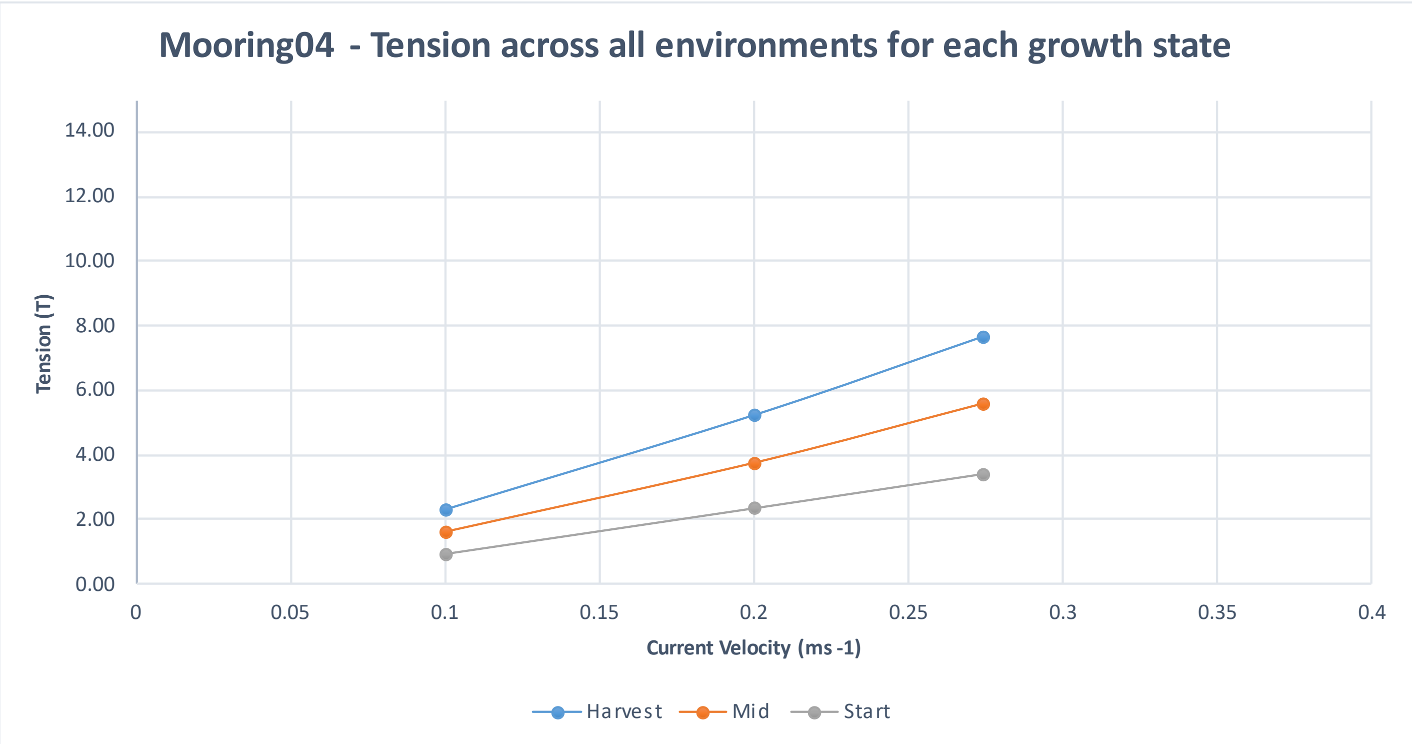


Figure 5 - Highest Loads in Mooring04 across all states

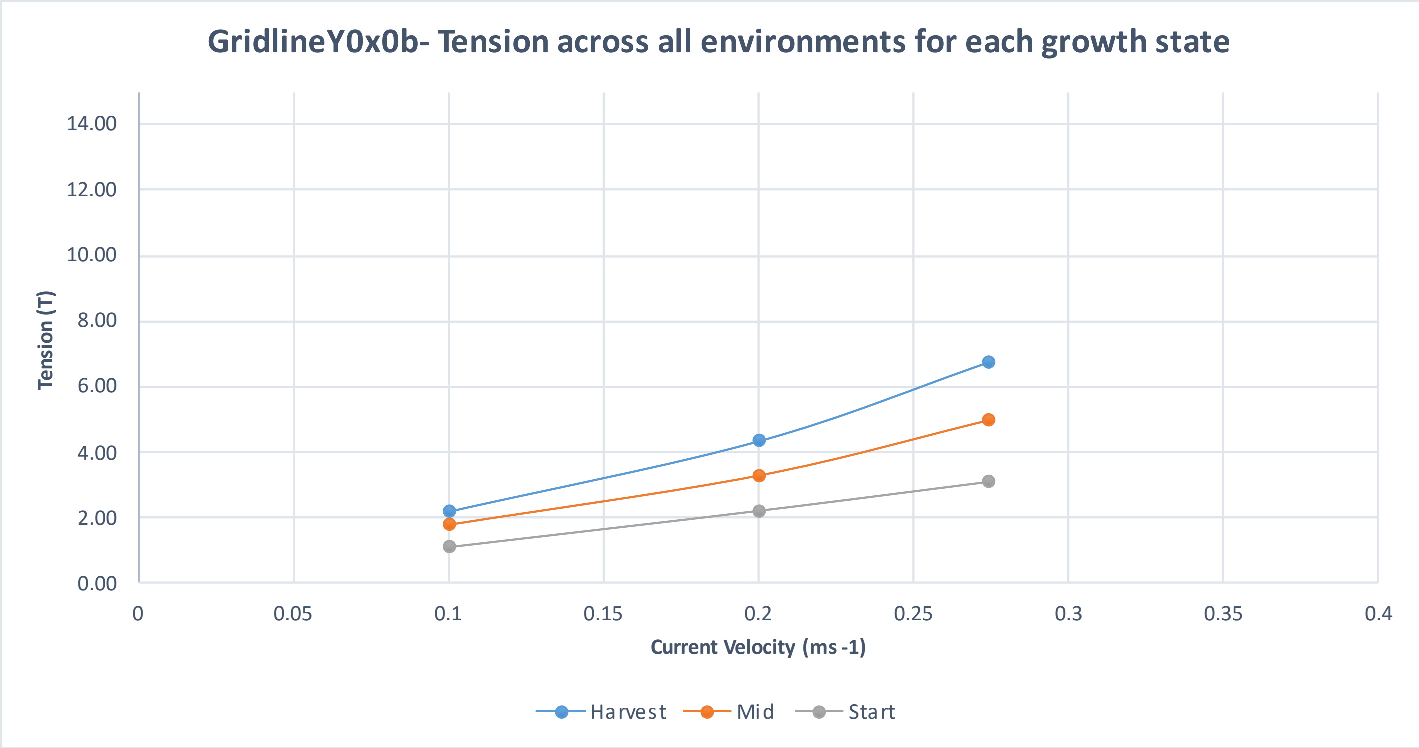


Figure 6 - Highest loads in GridlineY0x0b across all states

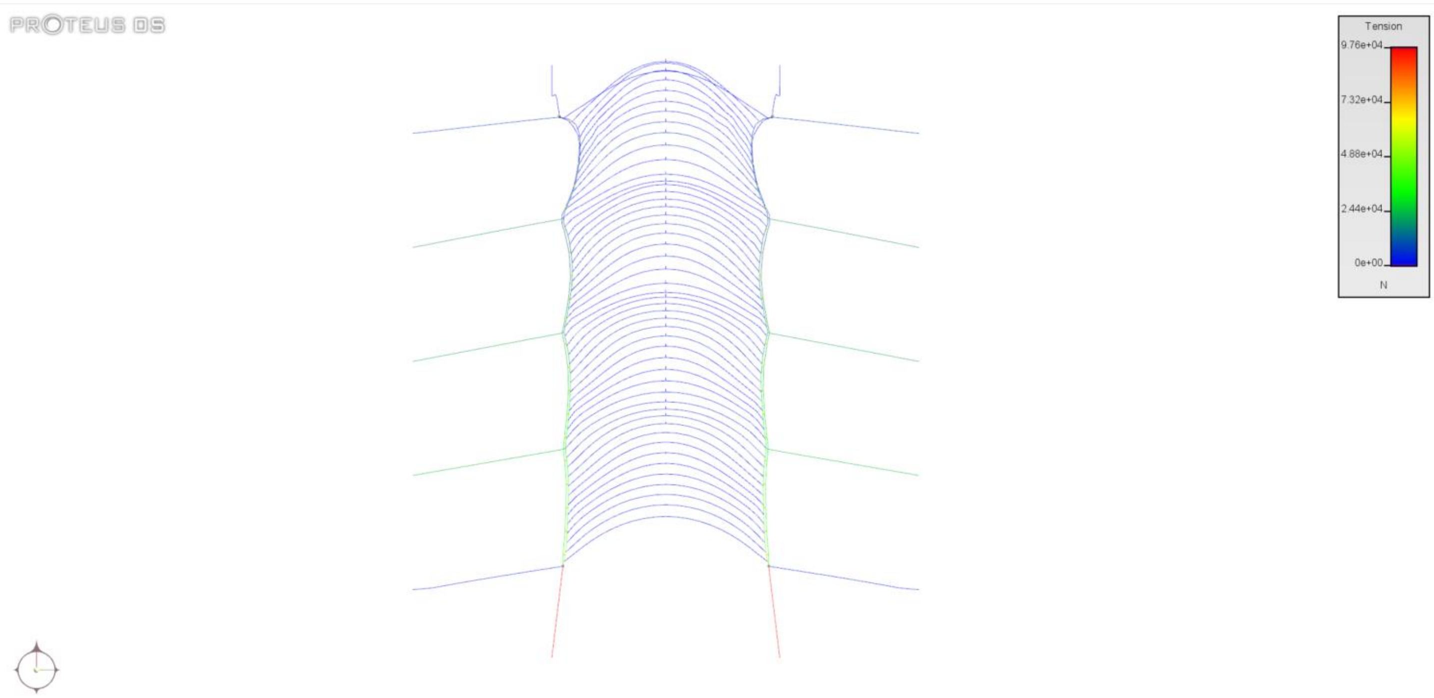


Figure 7 - ULS01 - Tension

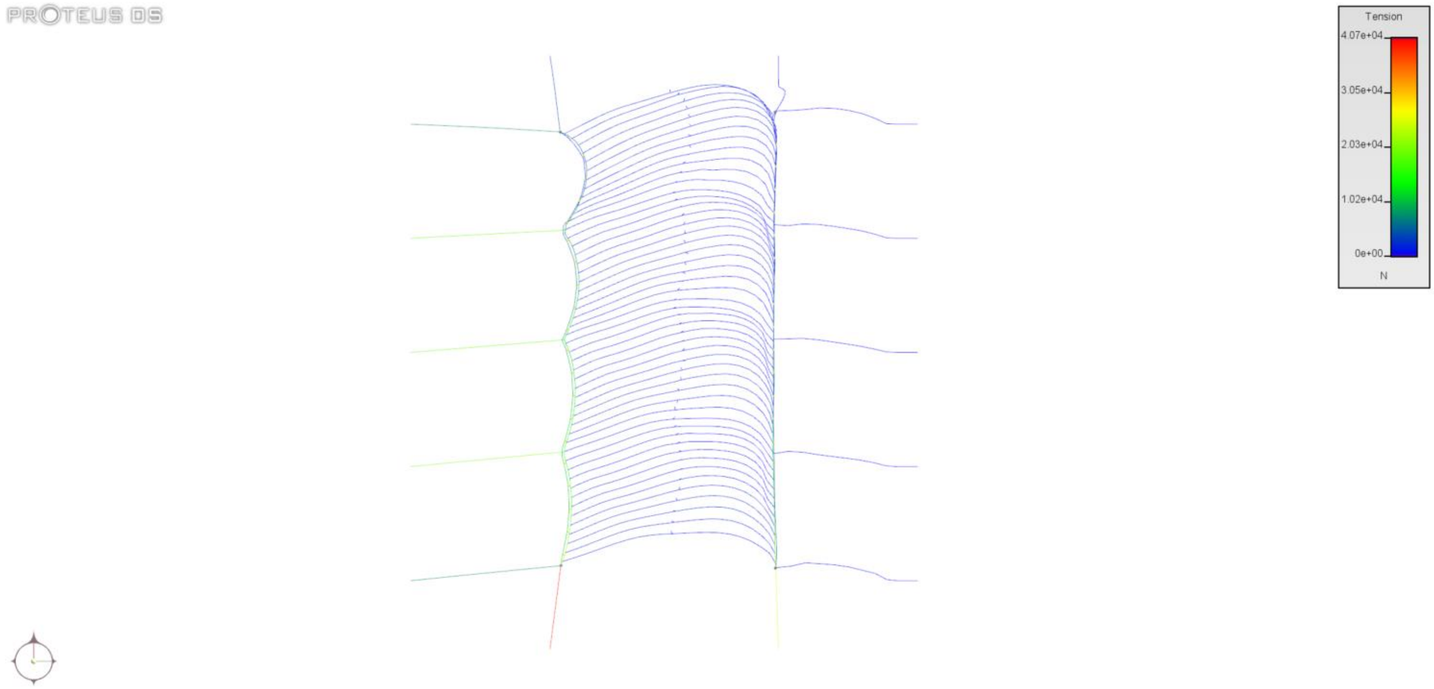


Figure 8 - ULS02 - Tension

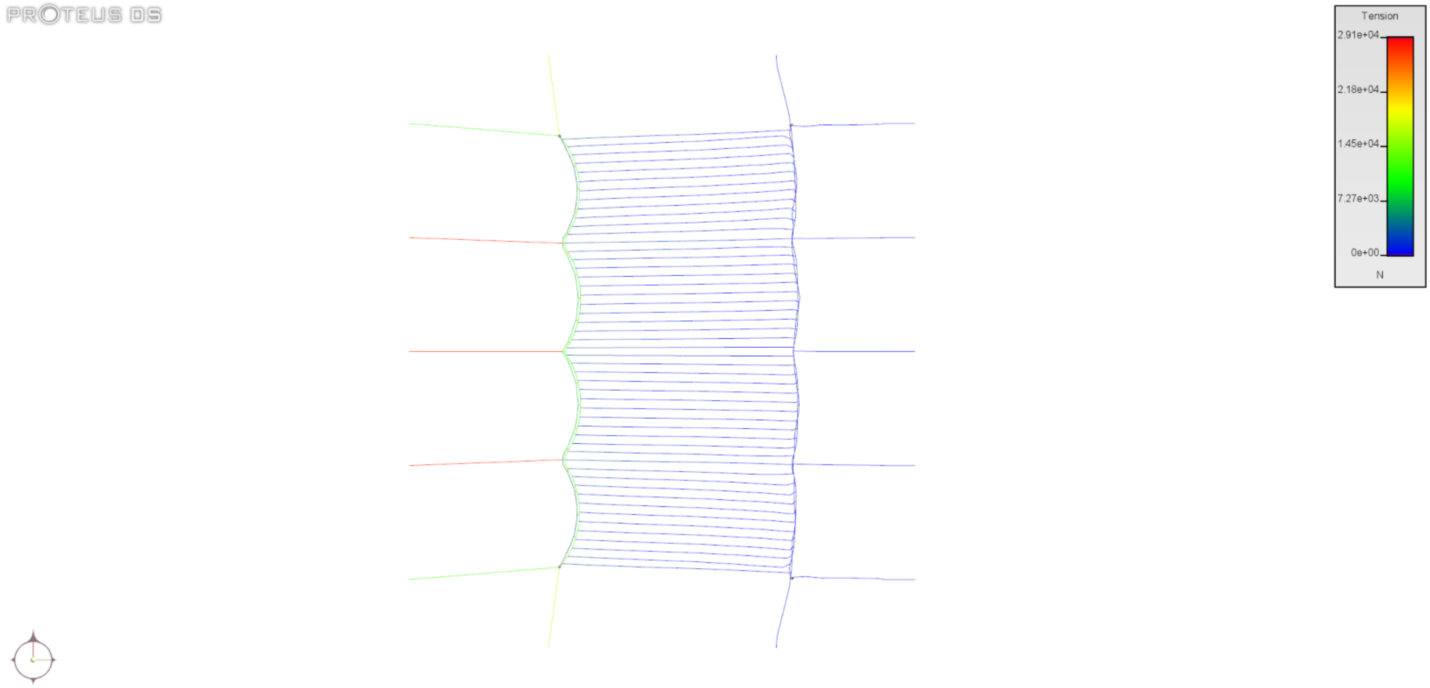


Figure 9 - ULS03 - Tension

4.2.3 Buoys – Submersion

In the simulations a virtual probe is located in all buoys enabling the buoy submersion to be recorded. Table 13: Highest Buoy Submersion identifies the maximum submersion each buoy experiences and the study in which it experiences it.

Table 13: Highest Buoy Submersion in Harvest State – Environment 1

Buoy No.	Study With Deepest Submersion	Submersion (m)
EB0x0	ULS01_Harvest_0	-7.60
EB0x1	ULS05_Harvest_180	-7.60
EB1x0	ULS01_Harvest_0	**-7.60**
EB1x1	ULS05_Harvest_180	-7.60
MF0x01	ULS01_Harvest_0	**-7.67**
MF0x02	ULS01_Harvest_0	-6.03
MF0x03	ULS02_Harvest_45	-4.98
MF0x04	ULS02_Harvest_45	-4.44
MF0x05	ULS02_Harvest_45	-4.44
MF0x06	ULS03_Harvest_90	-4.08
MF0x07	ULS03_Harvest_90	-3.01
MF0x08	ULS03_Harvest_90	-2.65
MF0x09	ULS03_Harvest_90	-2.99
MF0x10	ULS03_Harvest_90	-4.00
MF0x11	ULS03_Harvest_90	-4.00
MF0x12	ULS03_Harvest_90	-2.99
MF0x13	ULS03_Harvest_90	-2.65
MF0x14	ULS03_Harvest_90	-3.01
MF0x15	ULS03_Harvest_90	-4.09
MF0x16	ULS04_Harvest_135	-4.44
MF0x17	ULS04_Harvest_135	-4.44
MF0x18	ULS04_Harvest_135	-4.98
MF0x19	ULS05_Harvest_180	-6.03
MF0x20	ULS05_Harvest_180	-7.67
MF1x01	ULS01_Harvest_0	-7.67
MF1x02	ULS01_Harvest_0	-6.03
MF1x03	ULS08_Harvest_315	-4.96
MF1x04	ULS08_Harvest_315	-4.42
MF1x05	ULS08_Harvest_315	-4.42
MF1x06	ULS07_Harvest_270	-4.09
MF1x07	ULS07_Harvest_270	-3.01
MF1x08	ULS07_Harvest_270	-2.65
MF1x09	ULS07_Harvest_270	-2.99
MF1x10	ULS07_Harvest_270	-4.00
MF1x11	ULS07_Harvest_270	-4.00
MF1x12	ULS07_Harvest_270	-2.99
MF1x13	ULS07_Harvest_270	-2.65
MF1x14	ULS07_Harvest_270	-3.00
MF1x15	ULS07_Harvest_270	-4.07
MF1x16	ULS06_Harvest_225	-4.42
MF1x17	ULS06_Harvest_225	-4.42
MF1x18	ULS06_Harvest_225	-4.96
MF1x19	ULS05_Harvest_180	-6.03
MF1x20	ULS05_Harvest_180	-7.67

The values highlighted in bold are the deepest submerged buoys of each type across all studies. The plot of these buoys have been provided in the following figures.

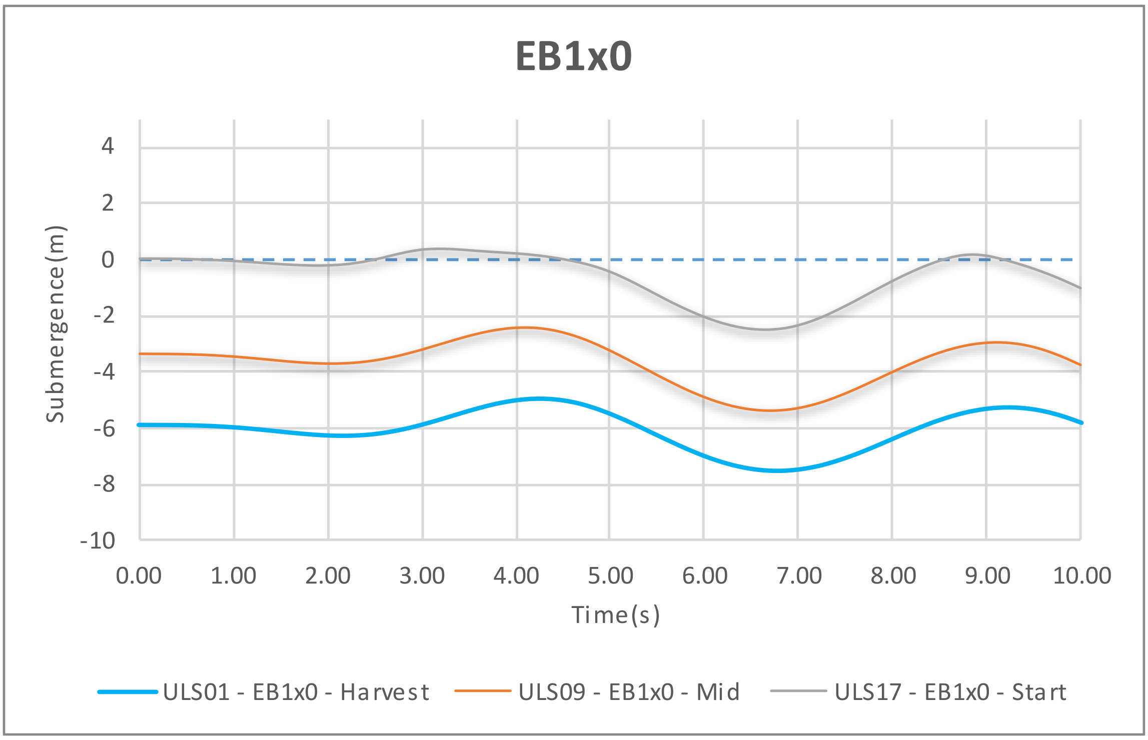


Figure 10 - Buoy Simulation – buoy EB1x0 submersion end buoy – Environment 1

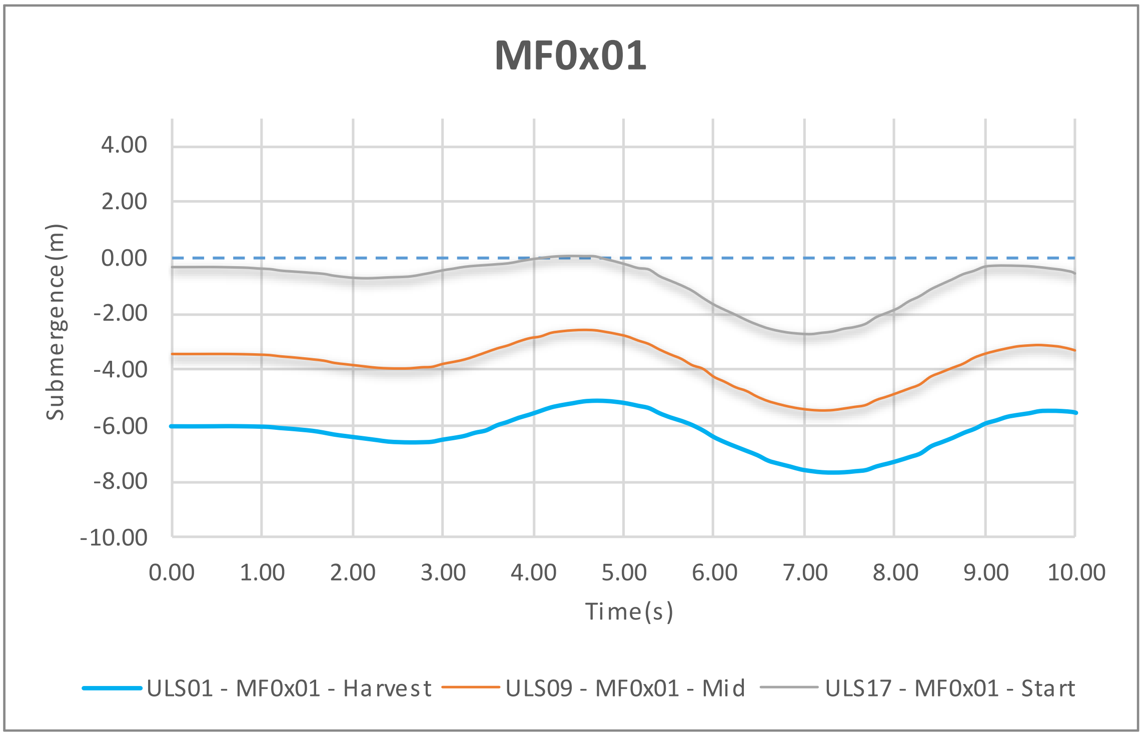


Figure 11 - Buoy Simulation – buoy MF0x01 submersion mussel floats – Environment 1

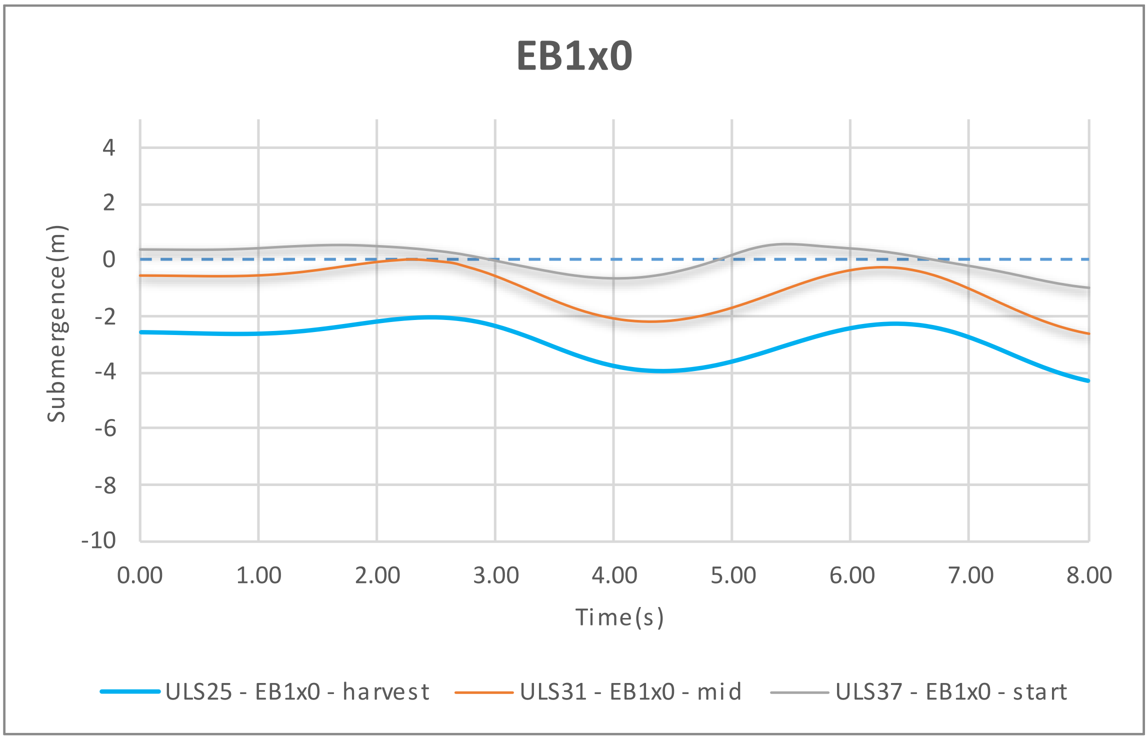


Figure 13 - Buoy Simulation – buoy EB1x0 submersion end buoy – Environment 2

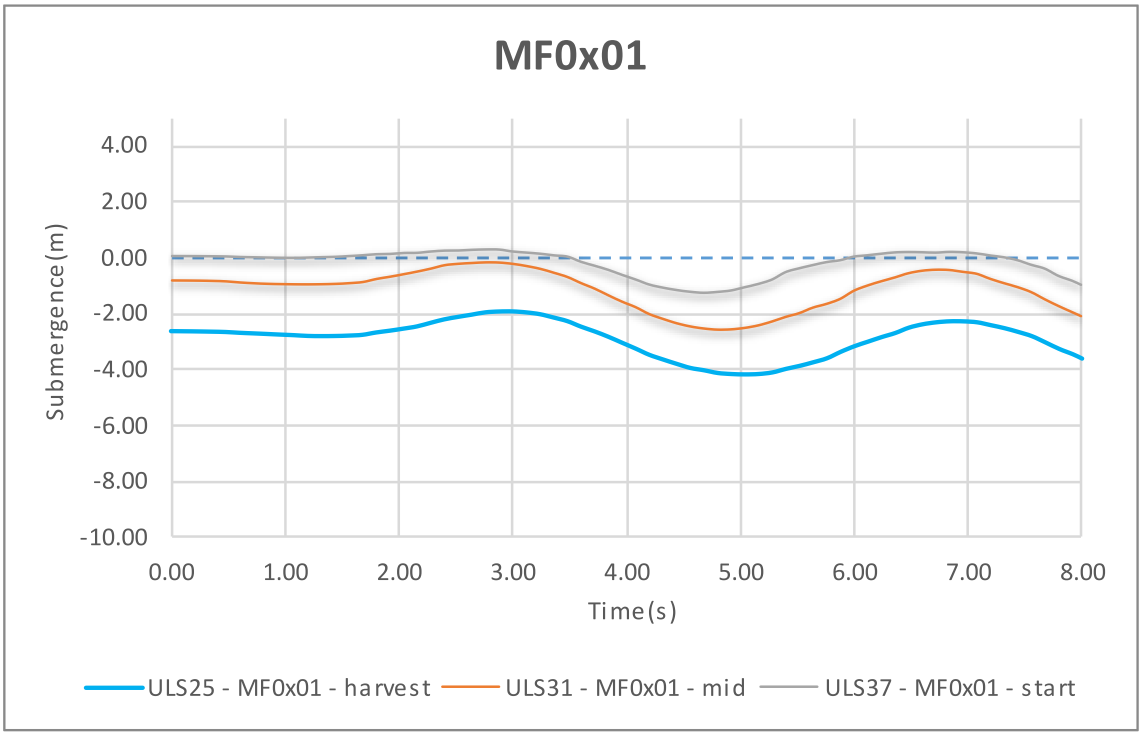


Figure 12 - Buoy Simulation – buoy MF0x01 submersion mussel floats – Environment 2

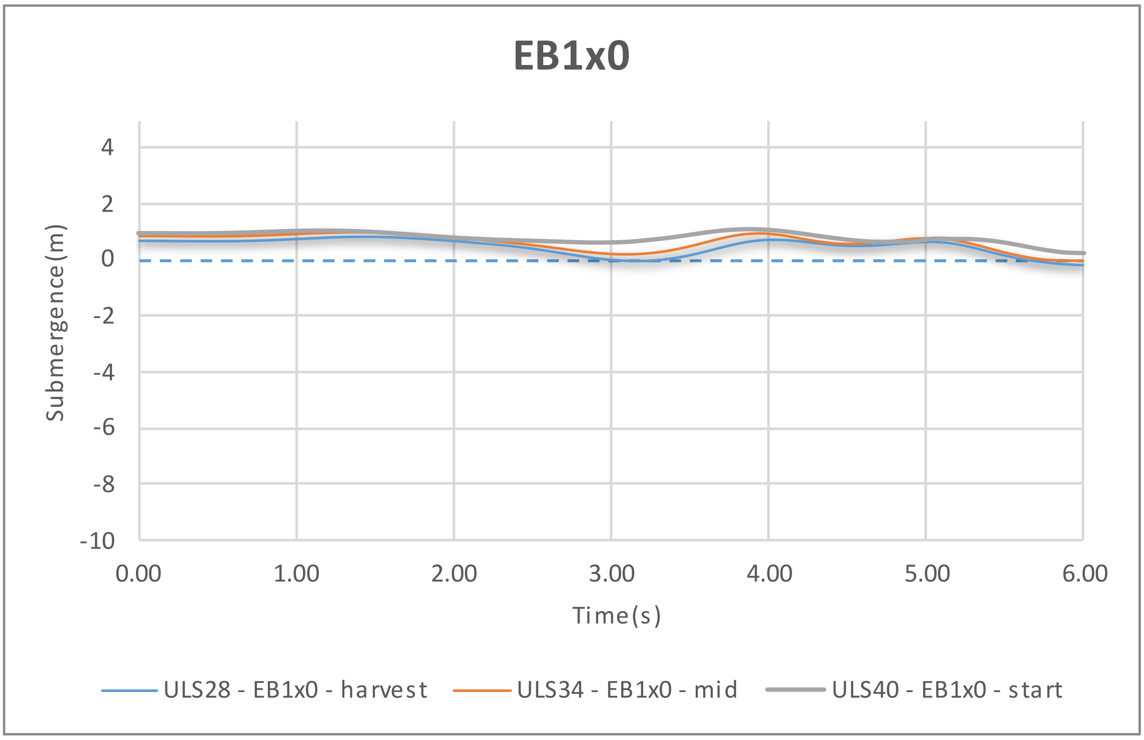


Figure 14 - Buoy Simulation – buoy EB1x0 submersion end buoy – Environment 3

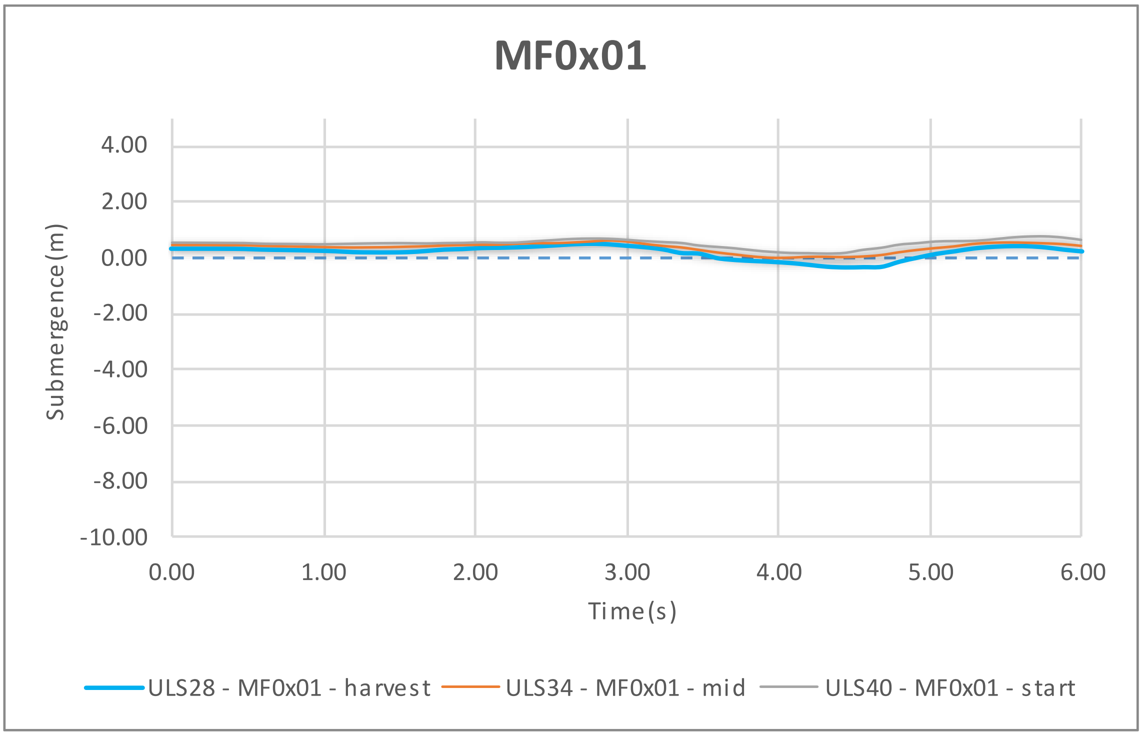


Figure 15 - Buoy Simulation – buoy MF0x01 submersion mussel floats – Environment 3

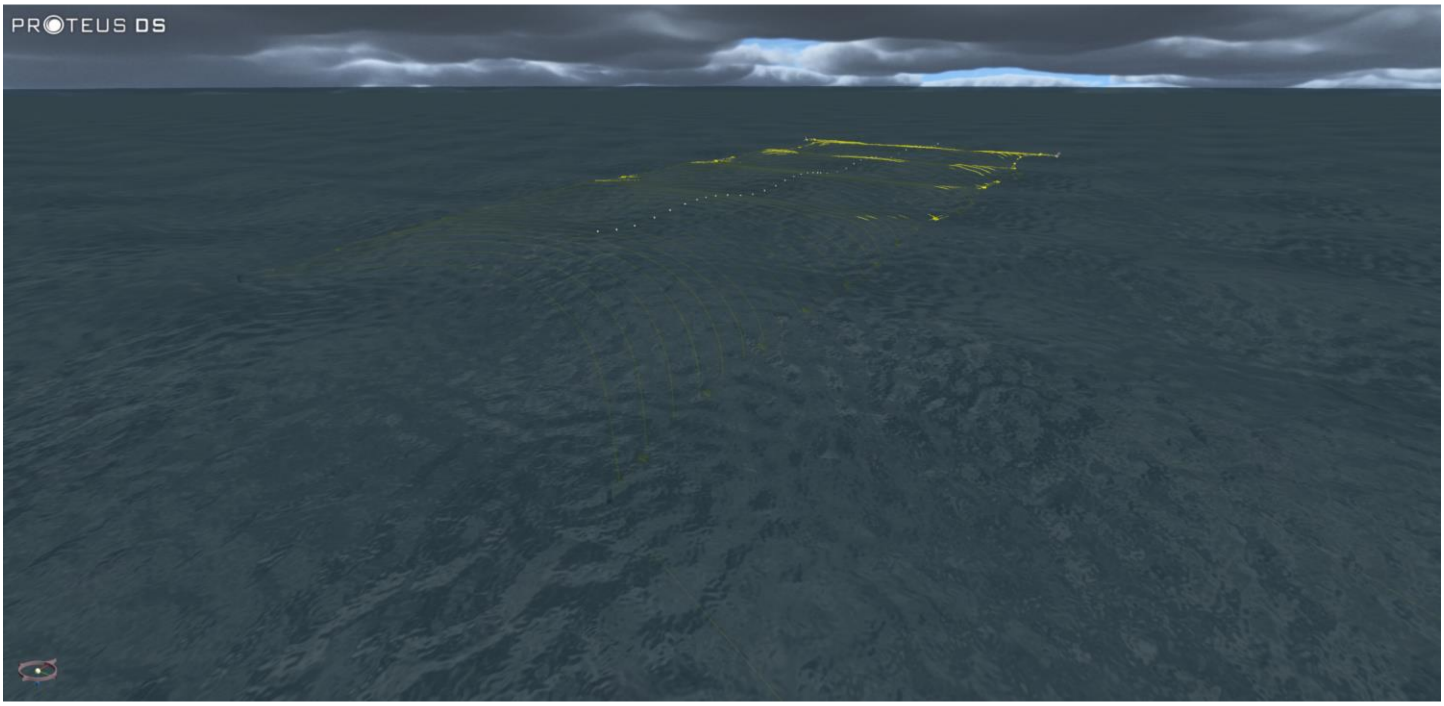


Figure 16 - ULS01 - Rendered View

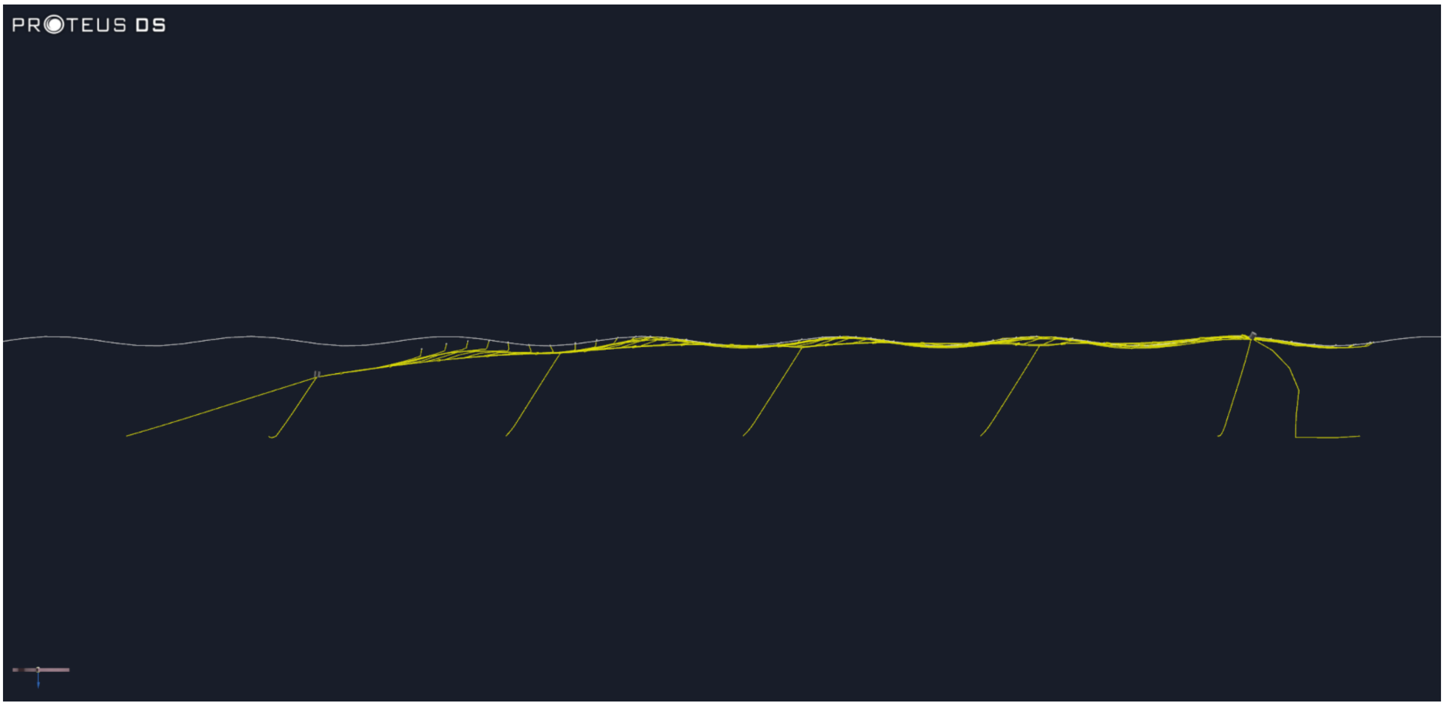


Figure 17 - ULS01 - Elevation

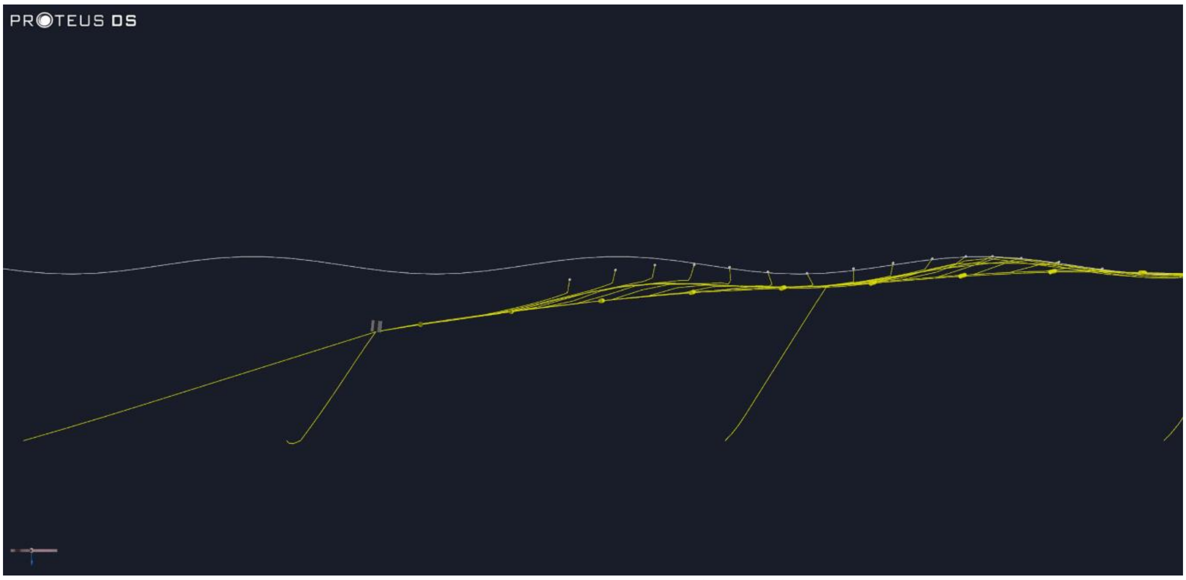


Figure 18 - ULS01 - End Buoy Submergence (harvest) – Environment 1

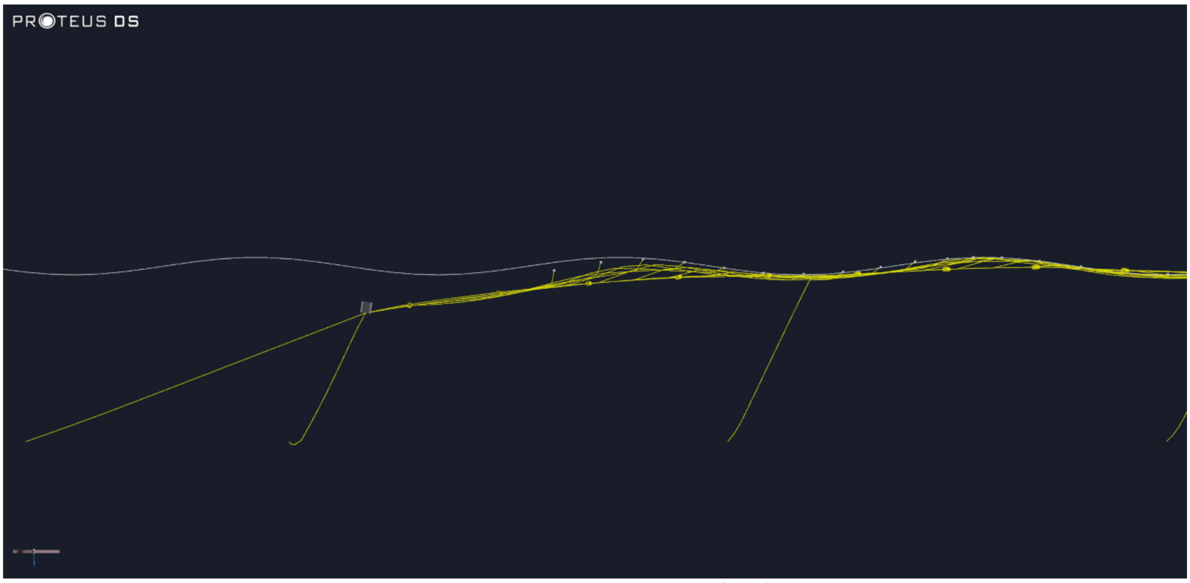


Figure 19 - ULS09 - End Buoy Submergence (mid) – Environment 1

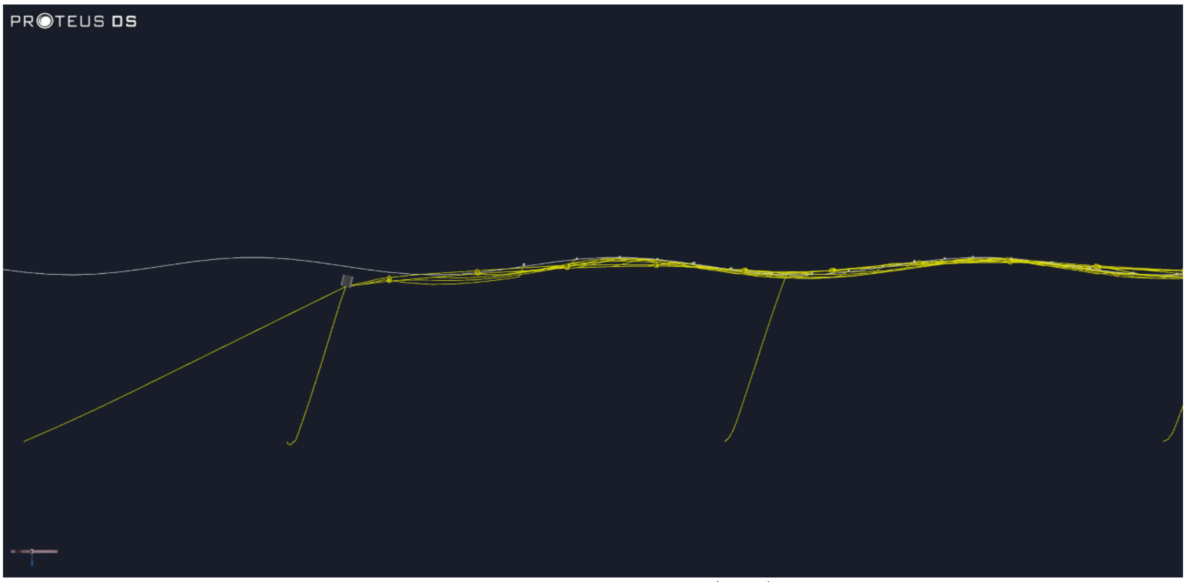


Figure 20 - ULS17 - End Buoy Submergence (start) – Environment 1

5 Minimum Safety Factors – Harvest State Across all Environments

Table 14: Mooring Line Minimum Safety Factors – Harvest state – Environment 1

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies								
Mooring	Segment	ULS01_Harvest_0	ULS02_Harvest_45	ULS03_Harvest_90	ULS04_Harvest_135	ULS05_Harvest_180	ULS06_Harvest_225	ULS07_Harvest_270	ULS08_Harvest_315	Min FOS ULS
Mooring01	PolySteel_3_Strand_32	**1.42**	2.44	40.76	>100	>100	29.40	4.00	1.83	**1.42**
Mooring01	U2_StudLink_32	**5.19**	8.94	>100	>100	>100	>100	14.62	6.68	5.19
Mooring02	PolySteel_3_Strand_32	**1.42**	1.83	4.00	26.54	>100	>100	37.71	2.47	1.42
Mooring02	U2_StudLink_32	**5.19**	6.68	14.63	97.11	>100	>100	>100	9.06	5.19
Mooring03	PolySteel_3_Strand_32	41.90	7.49	**4.29**	5.29	19.22	79.35	>100	>100	4.29
Mooring03	U2_StudLink_32	>100	27.40	**15.68**	19.34	70.34	>100	>100	>100	15.68
Mooring04	PolySteel_3_Strand_32	5.62	2.71	**2.12**	2.70	6.24	>100	>100	>100	2.12
Mooring04	U2_StudLink_32	20.57	9.93	**7.74**	9.89	22.85	>100	>100	>100	7.74
Mooring05	PolySteel_3_Strand_32	5.70	2.71	**2.15**	2.71	5.70	>100	>100	>100	2.15
Mooring05	U2_StudLink_32	20.86	9.91	**7.87**	9.90	20.87	>100	>100	>100	7.87
Mooring06	PolySteel_3_Strand_32	6.23	2.70	**2.12**	2.71	5.62	>100	>100	>100	2.12
Mooring06	U2_StudLink_32	22.80	9.89	**7.74**	9.93	20.57	>100	>100	>100	7.74
Mooring07	PolySteel_3_Strand_32	19.33	5.29	**4.29**	7.49	41.91	>100	>100	>100	4.29
Mooring07	U2_StudLink_32	70.75	19.35	**15.69**	27.40	>100	>100	>100	>100	15.69
Mooring08	PolySteel_3_Strand_32	>100	32.08	4.00	1.83	**1.42**	2.48	34.91	98.70	1.42
Mooring08	U2_StudLink_32	>100	>100	14.63	6.68	**5.19**	9.06	>100	>100	5.19
Mooring09	PolySteel_3_Strand_32	>100	>100	41.07	2.44	**1.42**	1.83	3.98	31.70	1.42
Mooring09	U2_StudLink_32	>100	>100	>100	8.94	**5.19**	6.68	14.58	>100	5.19
Mooring10	PolySteel_3_Strand_32	18.91	>100	80.62	>100	41.84	7.50	**4.26**	5.26	4.26
Mooring10	U2_StudLink_32	69.21	>100	>100	>100	>100	27.44	**15.59**	19.26	15.59
Mooring11	PolySteel_3_Strand_32	6.24	>100	>100	>100	5.62	2.72	**2.10**	2.70	2.10
Mooring11	U2_StudLink_32	22.82	>100	>100	>100	20.56	9.95	**7.69**	9.89	7.69
Mooring12	PolySteel_3_Strand_32	5.71	>100	>100	>100	5.71	2.72	**2.14**	2.72	2.14
Mooring12	U2_StudLink_32	20.91	>100	>100	>100	20.90	9.94	**7.84**	9.94	7.84
Mooring13	PolySteel_3_Strand_32	5.62	>100	>100	>100	6.25	2.71	**2.10**	2.72	2.10
Mooring13	U2_StudLink_32	20.57	>100	>100	>100	22.88	9.90	**7.70**	9.95	7.70
Mooring14	PolySteel_3_Strand_32	41.78	>100	>100	>100	19.11	5.28	**4.26**	7.50	4.26
Mooring14	U2_StudLink_32	>100	>100	>100	>100	69.91	19.31	**15.58**	27.44	15.58

Table 15: Grid Line Minimum Safety Factors – Harvest state – Environment 1

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies								
Gridline	Segment	ULS01_Harvest_0	ULS02_Harvest_45	ULS03_Harvest_90	ULS04_Harvest_135	ULS05_Harvest_180	ULS06_Harvest_225	ULS07_Harvest_270	ULS08_Harvest_315	Min FOS ULS
GridlineY0x0b	PolySteel_3_Strand_32	2.41	2.74	3.71	2.74	**2.41**	3.80	35.65	3.80	**2.41**
GridlineY0x1b	PolySteel_3_Strand_32	**3.90**	8.43	77.74	8.39	3.90	4.84	5.92	4.84	3.90
GridlineY0x0a	PolySteel_3_Strand_32	3.90	4.84	5.94	4.83	**3.90**	8.81	96.40	8.76	3.90
GridlineY0x1a	PolySteel_3_Strand_32	**2.41**	3.78	43.89	3.78	2.41	2.74	3.69	2.74	2.41

Table 16: Mooring Line Minimum Safety Factors – Harvest state – Environment 2

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies			
Mooring	Segment	ULS25_Harvest2_0	ULS26_Harvest2_45	ULS27_Harvest2_90	Min FOS ULS
Mooring01	PolySteel_3_Strand_32	**2.18**	3.80	46.24	**2.18**
Mooring01	U2_StudLink_32	**7.98**	13.89	>100	7.98
Mooring02	PolySteel_3_Strand_32	**2.18**	2.63	4.93	2.18
Mooring02	U2_StudLink_32	**7.99**	9.62	18.03	7.99
Mooring03	PolySteel_3_Strand_32	48.48	10.26	**6.11**	6.11
Mooring03	U2_StudLink_32	>100	37.53	**22.36**	22.36
Mooring04	PolySteel_3_Strand_32	9.20	3.87	**3.10**	3.10
Mooring04	U2_StudLink_32	33.65	14.18	**11.35**	11.35
Mooring05	PolySteel_3_Strand_32	10.31	4.05	**3.16**	3.16
Mooring05	U2_StudLink_32	37.74	14.82	**11.57**	11.57
Mooring06	PolySteel_3_Strand_32	11.19	4.03	**3.10**	3.10
Mooring06	U2_StudLink_32	40.97	14.76	**11.35**	11.35
Mooring07	PolySteel_3_Strand_32	23.14	7.43	**6.11**	6.11
Mooring07	U2_StudLink_32	84.68	27.18	**22.35**	22.35
Mooring08	PolySteel_3_Strand_32	>100	28.81	**4.92**	4.92
Mooring08	U2_StudLink_32	>100	>100	**18.01**	18.01
Mooring09	PolySteel_3_Strand_32	87.96	>100	**45.25**	45.25
Mooring09	U2_StudLink_32	>100	>100	>100	165.57
Mooring10	PolySteel_3_Strand_32	**23.17**	>100	>100	23.17
Mooring10	U2_StudLink_32	**84.77**	>100	>100	84.77
Mooring11	PolySteel_3_Strand_32	**11.13**	>100	>100	11.13
Mooring11	U2_StudLink_32	**40.74**	>100	>100	40.74
Mooring12	PolySteel_3_Strand_32	**10.30**	>100	>100	10.30
Mooring12	U2_StudLink_32	**37.68**	>100	>100	37.68
Mooring13	PolySteel_3_Strand_32	**9.20**	>100	>100	9.20
Mooring13	U2_StudLink_32	**33.66**	>100	>100	33.66
Mooring14	PolySteel_3_Strand_32	**48.04**	>100	>100	48.04
Mooring14	U2_StudLink_32	>100	>100	>100	175.82

Table 17: Grid Line Minimum Safety Factors – Harvest state – Environment 2

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies			
Gridline	Segment	ULS25_Harvest2_0	ULS26_Harvest2_45	ULS27_Harvest2_90	Min FOS ULS
GridlineY0x0b	PolySteel_3_Strand_32	**3.73**	3.95	5.38	**3.73**
GridlineY0x1b	PolySteel_3_Strand_32	**6.76**	17.27	83.16	6.76
GridlineY0x0a	PolySteel_3_Strand_32	**6.76**	7.52	8.52	6.76
GridlineY0x1a	PolySteel_3_Strand_32	**3.73**	5.23	56.60	3.73

Table 18: Mooring Line Minimum Safety Factors – Harvest state – Environment 3

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies			
Mooring	Segment	ULS28_Harvest3_0	ULS29_Harvest3_45	ULS30_Harvest3_90	Min FOS ULS
Mooring01	PolySteel_3_Strand_32	**6.65**	20.34	54.71	6.65
Mooring01	U2_StudLink_32	**24.34**	74.42	>100	24.34
Mooring02	PolySteel_3_Strand_32	6.63	**5.67**	9.23	**5.67**
Mooring02	U2_StudLink_32	24.28	**20.73**	33.76	20.73
Mooring03	PolySteel_3_Strand_32	88.18	18.14	**12.85**	12.85
Mooring03	U2_StudLink_32	>100	66.38	**47.01**	47.01
Mooring04	PolySteel_3_Strand_32	51.67	8.44	**7.08**	7.08
Mooring04	U2_StudLink_32	>100	30.90	**25.89**	25.89
Mooring05	PolySteel_3_Strand_32	58.02	9.53	**7.26**	7.26
Mooring05	U2_StudLink_32	>100	34.87	**26.56**	26.56
Mooring06	PolySteel_3_Strand_32	48.73	9.68	**7.09**	7.09
Mooring06	U2_StudLink_32	>100	35.41	**25.96**	25.96
Mooring07	PolySteel_3_Strand_32	84.44	16.30	**12.84**	12.84
Mooring07	U2_StudLink_32	>100	59.64	**46.99**	46.99
Mooring08	PolySteel_3_Strand_32	>100	39.61	**9.36**	9.36
Mooring08	U2_StudLink_32	>100	>100	**34.24**	34.24
Mooring09	PolySteel_3_Strand_32	>100	>100	**53.81**	53.81
Mooring09	U2_StudLink_32	>100	>100	>100	196.90
Mooring10	PolySteel_3_Strand_32	**76.47**	>100	>100	76.47
Mooring10	U2_StudLink_32	>100	>100	>100	279.84
Mooring11	PolySteel_3_Strand_32	**42.82**	>100	>100	42.82
Mooring11	U2_StudLink_32	>100	>100	>100	156.69
Mooring12	PolySteel_3_Strand_32	**47.39**	>100	>100	47.39
Mooring12	U2_StudLink_32	>100	>100	>100	173.40
Mooring13	PolySteel_3_Strand_32	**47.03**	74.75	>100	47.03
Mooring13	U2_StudLink_32	>100	>100	>100	172.10
Mooring14	PolySteel_3_Strand_32	94.88	**72.90**	>100	72.90
Mooring14	U2_StudLink_32	>100	>100	>100	266.79

Table 19: Grid Line Minimum Safety Factors – Harvest state – Environment 3

Values highlighted in red are the minimum Factor of Safety for that component across all scenarios.

		FOS of Studies			
Gridline	Segment	ULS28_Harvest3_0	ULS29_Harvest3_45	ULS30_Harvest3_90	Min FOS ULS
GridlineY0x0b	PolySteel_3_Strand_32	9.94	**7.37**	10.80	**7.37**
GridlineY0x1b	PolySteel_3_Strand_32	**28.18**	74.17	>100	28.18
GridlineY0x0a	PolySteel_3_Strand_32	29.41	19.01	**18.22**	18.22
GridlineY0x1a	PolySteel_3_Strand_32	**9.70**	21.83	60.68	9.70

6 Conclusion

The design has been evaluated in accordance with Scottish Technical Standard for Finfish Aquaculture. The tables below show the highest loaded lines in the harvest state of environment 1 and their factors of safety compared with the requirement of the standard for a given material.

Line	Segment	Max Tension ULS (T)	Min FOS ULS	Found in	ULS Material Factor
Mooring02	PolySteel_3_Strand_32	11.44	1.42	ULS01	3.00
	U2_StudLink_32	11.44	5.19	ULS01	2.00
GridlineY0x0a	PolySteel_3_Strand_32	4.17	3.90	ULS01	3.00
GridlineY0x0b	PolySteel_3_Strand_32	6.75	2.41	ULS01	3.00

Definitions

10-year data	A statistical evaluation of the probable conditions which will occur at the given location in a ten-year period. 10-year data is linked to and will always have lower values than 50-year data.
50-year data	A statistical evaluation of the probable conditions which will occur at the given location in a fifty-year period. 50-year data is linked to and will always have higher values than 10-year data.
Dynamic Analysis	Evaluation of the system taking account of the change of loads over time through such characteristics as wave loading.
Element	The smallest section of a line which is utilised for the evaluation of loads on that line.
Finite Element Analysis (FEA)	The process of breaking down all lines into small discrete elements allowing the calculation of loads and stresses to be undertaken on a complex system. The loads calculated at the end of the element are used as the input loads to the adjoining element, therefor allowing repetition of the process through the complete system.
H_{max}	Maximum wave height (trough to crest) within the spectrum which makes up the significant wave height, for the purpose of modelling this is calculated as 1.9 x H_s
H_s	Significant wave height, the mean wave height (trough to crest) of the highest third of the waves.
Line	A rope, chain, strop or combination thereof which connects nodes within the mooring system, such as a mooring line, which connects an anchor to a connection on the grid.
Minimum Break Load (MBL)	The minimum guaranteed load which a component will carry before failure.
Safety Factor	The MBL of a component divided by the highest load applying upon it.
Segment	The section of a line made up by a single material, for example a mooring line may be made up of both chain and rope, it will therefore have two segments, one segment will be the length of the chain, the other segment will be the length of the rope.
Submersion	Distance below the surface of the water.

T_p	Wave period
Ultimate Limit State	Evaluation of the system in its normal, fully intact operating state.
γl	Load Factor, a safety factor applied to components to take account of the uncertainty or error involved in calculating loads. Specified within the applicable Standard.
γm	Material Factor, a safety factor applied to components to take account of the variation in materials when manufacturing components. Specified within the applicable Standard.

References

(1) Marine Scotland: A Technical Standard for Scottish Finfish Aquaculture

(2) https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2722144/OMAE2019-96375.pdf?sequence=1